Massive Star Mergers: Induced Mixing and Nucleosynthesis

N.Ivanova and Ph.Podsiadlowski
Astrophysics, Oxford University

Abstract. We study the nucleosynthesis and the induced mixing during the merging of massive stars inside a common envelope. The systems of interest are close binaries, initially consisting of a massive red supergiant and a main-sequence companion of a few solar masses. We apply parameterized results based on hydrodynamical simulations to model the stream-core interaction and the response of the star in a standard stellar-evolution code. Preliminary results are presented illustrating the possibility of unusual nucleosynthesis and post-merging dredge-up which can cause composition anomalies in the supergiant's envelope.

Keywords: Stars: evolution; stars: nucleosynthesis

1. Introduction

Common envelope (CE) evolution is one of the most interesting evolutionary stages of an initially close binary. It occurs when the two components of a binary system orbit inside an extended common envelope which is not in synchronous rotation with the embedded binary (Iben & Livio, 1993). A binary encounters a CE phase by one of three suggested channels: (1) a dynamical instability (Darwin instability) or a secular tidal instability (Hut, 1980; Lai, Rasio & Shapiro, 1993), (2) in nova systems because of the expansion of the nova shell engulfing the companion, and (3) as a consequence of dynamical mass transfer. Once a common envelope has formed, the secondary continues orbiting around the core of the primary within this common envelope. As the secondary is affected by various drag forces due to its interaction with the envelope, the orbit of the binary slowly shrinks. The transfer of angular momentum from the orbital motion to the envelope causes the spin-up of the envelope. The final result of this slow spiral-in depends on how much of the released orbital energy has been deposited into the envelope compared to the binding energy of the envelope. The deposited frictional energy may drive expansion of the envelope, causing its partial or complete ejection. If most of the envelope is ejected, the system survives as a close binary consisting of the core of the primary and the secondary. This evolutionary path provides the favourite channel for the formation of short-period binaries with compact components.

Here we are primarily interested in the situation where the deposited energy is not sufficient to eject the common envelope. Then the spiral-in continues until the secondary starts to fill its own Roche lobe and begins

to transfer mass to the core of the giant. Eventually, the binary will merge resulting in the formation of a rapidly rotating single star. During this merger, material from the secondary forms a stream which emanates from the secondary and falls towards the primary core, encountering an ambient medium with increasing pressure and density. This hydrogen-rich material may penetrate to a depth of about 10^{10} cm where the temperature of the ambient matter is as high as a few 10^8 K. This deep penetration may have two major consequences: (a) the initiation of hydrogen burning through the hot-CNO cycle which may provide a neutron flux sufficient for efficient s-processing; (b) the injection/generation of high-entropy material near the primary core which may lead to the dredge-up of helium, eventually changing the surface composition of the merger product. In this contribution we present some preliminary results of the evolutionary calculations which involve the modelling of the merging phase.

2. Modelling the binary merger

Modelling the merging process requires consideration of many different aspects. The first is the response of the envelope of the primary due to the presence of the secondary. This includes modelling the gravitational effect of the primary, the luminosity generated by the accretion onto the secondary and the frictional luminosity due to the differential rotation of the common envelope (see Meyer and Meyer-Hofmeister 1979; Hjellming and Taam 1991; Ivanova, Podsiadlowski and Spruit, 2000). A second important aspect is how to describe the gas flow from the secondary, in particular, the entropy of the stream material and the depth to which this flow can penetrate into the core of the primary. This also requires the self-consistent determination of the mass-loss rate from the embedded secondary into the common envelope, the density of the stream and the change of this entropy due to the interaction with the ambient medium (Ivanova, Podsiadlowski & Spruit, 2001, IPS)

In our evolutionary simulations we follow a simplified scenario for the spiral-in, taking into account all of these effects. To model the deposition of hydrogen-rich material in the core of the primary, we use the prescription developed in IPS: this recipe provides an estimate for the penetration depth based on a modified Bernoulli integral and the entropy change of the stream material for a parameterized stellar structure, where the entropy change in the post-shocked material comapre to the initial state is calculated as

$$K_{\mathrm{S}} = \frac{P_{\mathrm{s}}}{P}\left(\frac{\rho_{\mathrm{s}}}{\rho}\right)^{\gamma} = 1 + k \cdot \eta_{\rho}^{\gamma-1}\left(\frac{M_{\mathrm{int}}}{M_{\mathrm{ext}}}\right)^2 \ .$$

Here η_ρ is the ratio of the stream density to the density of the ambient matter, M_{int} and M_{ext} are internal and external Mach numbers of the stream, γ is the adiabatic index of the stream material. For our calculations we used the entropy change coefficients in the range $0 \div 0.4$.

Special considerations need to be taken in the calculations of nuclear reactions within the stream-core impact region, where a convective zone can develop. The standard assumption in calculating nuclear reactions in evolutionary codes is that nuclear processes in convective regions occur on timescales which are much longer than the mixing timescale and that material is mixed efficiently in convective zones so that no abundance gradient can develop there. In the case where hydrogen-rich material is injected directly into the hot zone, the characteristic timescale of the hot-CNO cycle can be comparable to the timescale of the convective mixing. A method which can properly treat nucleosynthesis in this environment has been developed by Cannon (1993) for Thorne–Żytkow objects. For our merger simulations we use this method directly in the evolutionary code for stages starting with the merging itself up to the moment when the post-merging chemical composition is uniformly mixed over convective zones in the star, well after the merger has been completed.

As a starting point for the merger calculations we use a binary consisting of a $18\,M_\odot$ primary and a $2\,M_\odot$ secondary. The primary at the start of the spiral-in has been evolved to the stage where it has a core of about $6.8\,M_\odot$ (and a He-exhausted core of about $4.1\,M_\odot$). The secondary is then assumed to spiral-in inside the envelope of the primary, and the merger phase starts when the immersed secondary begins to overfill its Roche lobe. Since a primary application for this scenario is modelling the progenitor of SN 1987A, we adopted a chemical composition consistent with the composition of young stars in the LMC, with $X = 0.71$ and $Z = 0.01$. We chose a mixing-length parameter $\alpha = 2$ and included convective overshooting and undershooting by 0.25 pressure scale heights.

3. Results and discussion

In our preliminary runs we have calculated two models, one with no entropy change in the stream and one with a high entropy change. The main differences between the two calculations can be explained in terms of how the hydrogen-rich material is injected into the hot, He-burning zone. In the case of no entropy change, the stream penetrates into the convective He-burning zone directly. This leads to an immediate very energetic response with very efficient nucleosynthesis. This causes a rapid expansion of the core of the primary and results in the widening of the secondary orbit and a temporary interruption of the mass transfer.

If there is large generation of entropy in the stream, $k = 0.4$, the stream cannot penetrate as deep and does not reach the convective He burning zone at the start of mass transfer. Since there is no dramatic expansion of the primary core, mass transfer continues steadily at an approximately constant rate. In the impact zone, a high-entropy region is generated. With time, a convective zone just below the impact zone starts to develop. Once created, this zone slowly erodes the core, mixing hydrogen down into hotter layers. The growth of this convective zone proceeds exponentially, very slow at the beginning, speeding up steadily up to the moment where it connects to the He-burning convective zone. At that point, hydrogen is quickly mixed throughout the He-burning zone. Unlike the previous case, the primary at this stage has accumulated much more hydrogen in this zone, which therefore leads to much more dramatic nuclear burning when the hydrogen is mixed into the helium-burning zone.

There are many uncertainties which can affect and significantly change these results. The models discussed above have been calculated with the assumption that there is significant convective undershooting. Nevertheless, calculations which have been done for a smaller entropy change ($k = 0.2$) but without undershooting have shown a behavior similar to the behaviour in the second model; but the model with $k = 0.4$ and no undershooting did not show any mixing of hydrogen into the helium-burning zone, though the entropy generated in the core neighborhood during the merger can still induce mixing at a later stage. Another possible uncertainty is the speed of mixing in the convective zones, as it affects the rate with which the hydrogen-rich material is moving into the hot zone, which affects the nucleosynthesis.

Our preliminary conclusion is that, during the merger, hydrogen-rich material from the secondary may be able to penetrate into the He-burning zone, though in the case of high-entropy generation in the stream, it is likely to happen only if there is significant undershooting.

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